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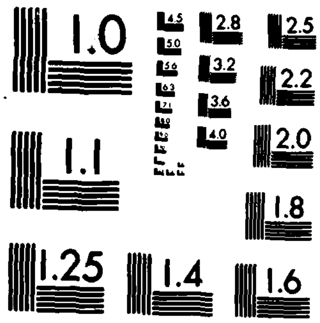

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INVESTIGATION OF SUPERRADIANT LDV MARKERS AND THREE-COMPONENT VELOCITY MAPPING

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The major progress in the first year of AFOSR support has been made in the area of laser interactions with micron-size droplets flowing in a linear stream. Motivated by our interest in finding bright fluorescent markers for LDV instruments, we have continued the stud_ of lasing droplets. Magnified photographs of lasing droplets reveal that the laser radiation is confined just within the liquid-air interface, whether the actual droplet shape is spherical or spheroidal. The possibility of providing chemical species identification of liquid droplets from the nonlinear optical spectra of droplets led us to investigate the stimulated Raman scattering, coherent anti-Stokes Raman scattering, and coherent Raman mixing processes within the droplets. Progress in these areas is described.

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19. Abstract (Cont'd)

Considerable effort was devoted to developing an optical technique which has the potential of providing three-component velocity mapping in three dimensions. Double-pulse holographic experiments are currently under way with seeded particles in a cold flow. The observed particle tracks are being analyzed by a novel application of the Hough transform which is well known in the pattern recognition field. Progress in this area is also discussed.

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RESEARCH OBJECTIVES

Following is a brief description of our three principal research objectives.

1. To investigate the possibility of using lasing markers which are of interest in the flow diagnostics field. The conventional LDV technique relies on the elastic scattering from a single marker which traverses the interference pattern created by two laser beams. In highly turbulent environments or at locations near a solid surface, the background elastic scattering can overwhelm the elastic scattering from a single marker. The wavelength-shifted emission from the lasing markers can be optically isolated from the nonwavelength-shifted background caused by the turbulent medium and/or the container walls.
2. To investigate the possibility of using nonlinear optical spectroscopy [such as stimulated Raman scattering (SRS), coherent anti-Stokes Raman scattering (CARS), and coherent Raman mixing (CRM)] to provide molecular specific information within a single droplet. In-situ optical diagnostic techniques which can provide chemical species specific information on multicomponent liquid sprays are of interest in two-phase combustors.
3. To investigate the possibility of combining double-pulse laser volume holography and optical pattern recognition schemes to determine the spatial displacement of many markers in a large sample volume during t and $t + \Delta t$. Simultaneous determination of the three components of velocity from multiple points in a three-dimensional flow is highly desirable in combustion/turbulence diagnostics.

RESEARCH STATUS

Our research results for the first year of the project can be summarized as follows:

1. Lasing Droplets

Following our work reporting on laser emission from individual droplets [Opt. Lett. 9, 499 (1984)], we have continued our investigation on other lasing characteristics of droplets. Microscope enlarged photographs of individual lasing droplets reveal that, regardless of the droplet shape and size, the laser fields are confined just within the liquid-air interface and thereby highlight the interface. Furthermore, enlarged photographs of the elastically scattered radiation reveal two bright spots, one near the entrance face and another near the exit face. Both the laser emission and the elastic scattering provide considerable insight into the internal field distributions of the incident pump field and of the lasing field. Such internal field distributions will be helpful in formulating the theory for lasing droplets. Our results are described in a paper (with color photographs of the elastic and lasing emissions) to be published shortly in Science (publication #1, page 7). A review of the use of lasing droplets for droplet size and shape determination will be published in the Proceedings of an SPIE Conference (publication #2).

2. Nonlinear Optical Spectroscopy of Droplets

After reporting our results on SRS from ethanol and water droplets [Opt. Lett. 10, 37 (1985)], we have continued our studies on other forms

of nonlinear optical spectroscopy. In particular, we investigated the extent to which morphology-dependent resonances (MDR's) of a spherical droplet can influence four-wave mixing processes. Since CARS has been the most widely used nonlinear spectroscopic technique for temperature and species determination in gas phase combustion, we were particularly interested in knowing whether CARS can be observed from a single droplet and whether MDR's can enhance the CARS intensity. We also investigated another four-wave mixing process (CRM) which can provide additional gain to the stimulated Raman process. Both CARS and CRM require wave-vector phase matching, which we found to be important even in micron-size droplets, in spite of their short interaction lengths.

CARS was observed from individual micron-size droplets. However, to our surprise and disappointment, the MDR's which greatly enhance the SRS emission, did not influence the CARS spectra or the CARS output intensity. Whether the two incident wavelengths or the CARS wavelengths satisfied the MDR's or not, the CARS spectra and the CARS intensity were not affected. We have concluded that the phase-matching requirement associated with the four-wave mixing process is not commensurate with the MDR's, i.e., the phase-matching condition cannot be fulfilled for the waves circumventing the droplet interface. Phase matching can be satisfied only along the propagation directions of the two incident waves. Detailed accounts of our studies on CARS and CRM have been published in Optics Letters (publications #3 and #4).

SRS from organic liquid droplets was investigated with a low-dispersion spectrograph and a linear array detector. For CCl_4 droplets, up to 14th-order Stokes peaks were observed in the SRS spectra from a

single droplet. The energy shift of the 14th-order Stokes was exactly 14 times the energy shift of the 1st Stokes, implying that these multi-order SRS emissions are caused by sequential pumping by the (n - 1)th Stokes to produce Raman oscillations at the nth Stokes. Such multi-order Stokes clearly illustrate how intense the internally generated Stokes fields can be and how much feedback the MDR's can provide at each of the multi-order Stokes wavelengths. The stimulated Raman process is an efficient form of producing heat since the SRS process causes vibrational transitions from $v = 0 \rightarrow v = 1$ and, upon relaxation to the $v = 0$ state, heat is created within the droplet. Our ultimate aim is to quantify how much droplet heating results from the SRS for droplets which are "totally transparent" at low intensity levels. Laser-induced heating can lead to droplet vaporization, electric field breakdown, and even droplet ignition. The multi-order Stokes results have been submitted for publication (publications #4 and #5).

Our report on increasing the sensitivity of a SIT vidicon, by placing an image intensifier in optical contact with the SIT was accepted for publication in Applied Optics (publication #6). The increased sensitivity of the SIT vidicon was helpful in detecting weak signals of the spatially resolved rotational CARS of N_2 in a flame. The intensified SIT could also be useful in detecting the relatively weak single-pulse CARS spectra from a single droplet.

3. Three-Component Velocity from Multiple Points in Three Dimensions

No publication has resulted from our research endeavors in this area. However, definite progress is being made in setting a double-pulse holography configuration which will enable us to monitor in a

large sample volume the displacements of many seeded particles between two laser pulses delayed in time by Δt. Presently, the first Q-switched second-harmonic Nd:YAG laser pulse has a coherence length large enough to provide a good holographic image throughout a sample volume of $5 \times 5 \times 5\ cm^3$. We are developing techniques to improve the coherence length of the second laser pulse which is controlled to fire at a delayed time Δt (some hundreds of microseconds later).

Significant progress has been made in developing an optical pattern recognition scheme to determine the spatial displacement of many markers, i.e., to determine the particle track length and direction for two pulses delayed by Δt. The basic approach is that the seeds in a moving jet are illuminated by a coded light source (a long-duration flash followed by a short-duration flash) and recorded on a pair of cameras oriented at right angles to each other to produce x-z and y-z images. The result is that each seed produces on both cameras an "i" pattern with length and direction determined by the seed velocity. From the patterns of the x-z and y-z images, the three-dimensional velocity components (v_x, v_y, and v_z) can be determined. The use of two digital cameras allows this data reduction without the need to process film.

This approach is made feasible by the novel application of the Hough transform, which allows us to determine in an efficient manner the existence, location, and orientation of straight-line segments in an image. Having determined that there is a line in the x-z image at a particular location and orientation, its length and direction can be determined to provide values for v_x and v_z. Values for v_y and v_z are determined from the y-z image and are paired with those in the x-z image

by the location and magnitude of v_z to produce the three-velocity components for a particular seed.

The above approach is being evaluated by both performing simulations and conducting experiments. The simulation results allow us to determine the specifications of the digital cameras (the resolution and sensitivity) that will be used in the eventual design. Simulations also are used to determine the limitations of the approach when the seed density is increased. The experiments employ the same algorithms developed for the simulations and also present refinements to the simulation model, such as a reduction of the image of the moving seed having a finite thickness to a unique straight line. We have thus far demonstrated the approach using a pair of images of a bent wire which has been painted to mimic the coded "i" motions of three seeds, which overlap in at least one image. The approach has indeed given the correct values of the three-velocity components. We are currently investigating the seeds (small glass spheres, TiO_2 powder, and glass balloons) to be used in the next series of experiments, which will be performed with 35 mm cameras and an open-shutter technique. This will determine the practical specifications of the two digital cameras for implementing a prototype system.

PUBLICATIONS

1. S.-X. Qian, J.B. Snow, H.-M. Tzeng, and R.K. Chang, "Lasing Droplets: Highlighting the Liquid-Air Interface by Laser Emission," Science, in press.
2. H.-M. Tzeng, M.B. Long, R.K. Chang, and P.W. Barber, "Size and Shape Variations of Liquid Droplets Deduced from Morphology-Dependent Resonances in Fluorescence Spectra," to be published in Proceedings of the SPIE Particle Sizing and Spray Analysis Conference, San Diego, CA, August 19-23, 1985.
3. S.-X. Qian, J.B. Snow, and R.K. Chang, "Coherent Raman Mixing and Coherent Raman Scattering from Individual Micrometer-Size Droplets," Opt. Lett. 10, 499 (1985).
4. R.K. Chang, S.-X. Qian, and J. Eickmans, "Stimulated Raman Scattering, Phase Modulation, and Coherent Anti-Stokes Raman Scattering from Single Micrometer-Size Liquid Droplets," to be published in Proceedings of the Methods of Laser Spectroscopy Symposium, Rehovot, Israel, December 16-20, 1985.
5. S.-X. Qian and R.K. Chang, "Multi-Order Stokes Emissions from Micrometer-Size Droplets," submitted to Phys. Rev. Lett.
6. J.B. Snow, J.-B. Zheng, and R.K. Chang, "Increased Sensitivity of a Vidicon Optical Multichannel Analyzer with a Detachable Electrostatic Image Intensifier," Appl. Opt., in press.

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